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Risk and uncertainty assessment of volcanic hazards

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11.1 Introduction

Over 600 million people live close enough to active volcanoes to have their lives disrupted if there are signs of unrest that might lead to eruption, and threatened when an eruption does occur. This estimate is an update of the analysis of Tilling and Peterson (1993) and Small and Naumann (2001) using 2009 World Bank population data. In comparison to other natural hazards, such as earthquakes and floods, the historic death toll from volcanoes is quite small. Since about 1500 CE the Smithsonian Global Volcanism Program database records about 200 000 in total, and slightly below 100 000 since 1900 CE (Simkin *et al*., 2001; Witham, 2005; Siebert *et al*., 2011). However, there have been a small number of infamous historic eruptions with horrific casualty figures, such as the destruction of St Pierre in 1902 by Mont Pelée volcano, Martinique, with 29 000 fatalities (Heilprin, 1903) and the burial of the town of Armero, Colombia by a volcanic mudflow in 1985, with 25 000 fatalities due to an eruption of Nevado del Ruiz (Voight, 1990).

Although volcano deaths and economic losses are historically small compared to earthquakes, floods and droughts, this is misleading. In the 1991 eruption of Mount Pinatubo in the Philippines, a mega-disaster was narrowly averted when tens of thousands of people were evacuated from the flanks of the volcano just in time; as a consequence, the largest explosive eruption of the twentieth century only caused a few hundred casualties (Newhall and Punongbayan, 1996a, 1996b). In the decade that followed, more than 200 000 people had to be permanently evacuated because their towns were buried by lahars. Many lahar warnings were issued, both long-term and immediate. Roughly 400 people were killed by lahars, but this is also a relatively small number compared to the 200 000.

Disruption to societies and associated economic costs due to volcanic activity has been considerable, although not so easily quantified as deaths. During the first few years of the volcanic emergency on the small island of Montserrat (caused by the eruption of the Soufrière Hills volcano that started in 1995) over 8000 people were evacuated from the island or left voluntarily, two-thirds of the total population, and the estimated economic losses by 1999 were estimated at about US$1 billion (Clay *et al*., 1999). In 1976 what turned out to be a quite limited phreatic eruption of La Soufrière volcano in Guadeloupe led to the evacuation of 73 000 people for over three months, major economic costs for the island

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(some persisting to the present day) and significant turmoil among scientists and politicians in France (Fiske, 1984). The economic impact of volcanism was again more recently highlighted, in 2010, when a relatively minor eruption of the Eyjafjallajökull volcano in Iceland resulted in disruption to flights in European air space, severe inconvenience for millions of passengers and impacts on business and losses that are estimated to be US$1.7 billion for the aviation industry (IATA, 2011).

Nowadays, there are many big cities and megacities growing close to highly dangerous volcanoes, thereby increasing vulnerability. Naples in Italy is perhaps the best known, but there are many more – another example is Jakarta (Indonesia), which is built in part on deposits of landslides and debris flows from Salak and possibly Pangrango volcanoes, eruptions of which were triggered in 1699 by a strong regional earthquake. Volcanism adversely affects such countries disproportionately. This is in part due to the large number of active volcanoes in low-income countries, but is also due to limited resources (e.g. volcano monitoring, emergency management), limited resilience and a limited capacity for recovery. The possibility of massive and unprecedented numbers of casualties being suffered in some city lying close to an erupting volcano (a super-eruption) is real, and growing.

To top this, a giant volcanic eruption is also the only natural hazard apart from meteor impact that is capable of creating a truly global catastrophe (Rampino, 2002; Sparks *et al*., 2005; Bryan *et al*., 2010). In terms of geological time, advanced human societies are very recent, and volcanological and archaeological evidence indicates that very large magnitude eruptions can have environmental consequences devastating to human populations. A counter view is provided by Grattan (2006).

Living with a volcano is part of everyday existence for many communities, which in general are becoming more vulnerable as populations expand, reliance on technology increases and the effects of other kinds of environmental stress mount. On the other hand, advances in volcanology are helping with the provision of early warning and to improve the management of volcanic emergencies. The analysis, assessment and communication of risk and uncertainty are central to all aspects of living with volcanoes and through avoidance of disaster and minimising deaths and losses when they erupt.

This chapter summarises the current state of knowledge on risk assessment for volcanism and discusses future developments and needs. Section 11.2 outlines the main kinds of volcanic hazard. Section 11.3 synthesizes the state-of-the-art in prediction, forecasting and early warning. Section 11.4 discusses approaches to hazard and risk assessment, including hazards zonation maps. Section 11.5 considers risk management and the communication of hazard and risk during volcanic emergencies. Section 11.6 concludes with a discussion of future outlooks and challenges.

11.2 Volcanic hazards

There are an estimated 550 historically active volcanoes and 1300 active volcanoes in the world, the latter defined somewhat arbitrarily as those having evidence of eruptions during

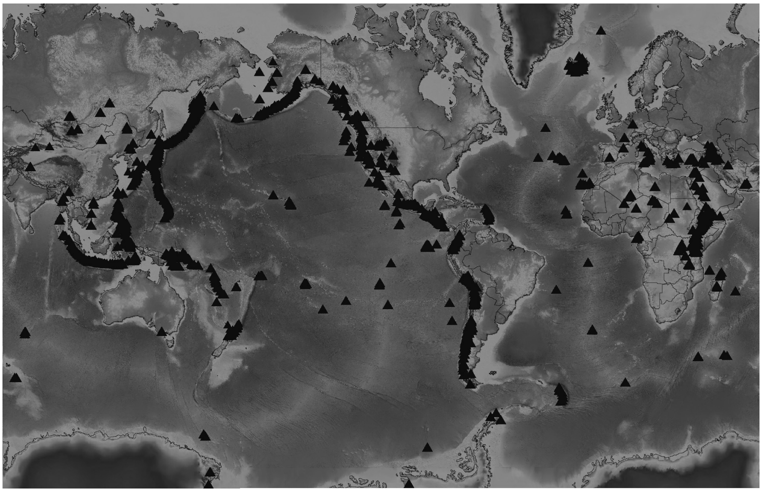

Figure 11.1 Distribution of the world's Holocene volcanoes.

the Holocene (last 10 000 years). About 20 volcanoes are erupting on average at any one time (see Siebert *et al*., 2011 for more authoritative information from the Smithsonian Institution's Global Volcanism Program). There are many more Quaternary volcanoes (defined as the last 2.58 million years) and it is likely that a significant number of these are dormant rather than extinct. Most volcanoes are located along plate tectonic boundaries and so coincide with places prone to large earthquakes (Figure 11.1).

Volcanoes come in all sorts of shapes and sizes and display a rich diversity of eruptive phenomena, so that hazard assessments have to consider several very different potential physical phenomena. Furthermore, each of these phenomena can range very widely in scale and intensity over several orders of magnitude and the footprint of a particular hazardous phenomenon is also highly variable as a consequence. Hazardous volcanic flows may be strongly dependent on topography, while ash hazards depend on meteorological factors. The different phenomena can occur simultaneously or can be causally linked, making volcanic hazards a rich and diverse subject that is quintessentially multi-hazard in character. Past activity is often a good guide to the future, but this is not always the case since volcanoes evolve and their eruptions can develop into new and sometimes unexpected eruptive regimes.

Eruptions span several orders of magnitude in terms of size, intensity and duration. Size is conventionally measured by the mass or volume of erupted material, which is defined as the magnitude (M). Like earthquakes and floods, the frequency of eruptions decreases markedly with magnitude, but this relationship is not yet very well characterised, partly because volume is often poorly constrained. As an example, the eruption of Mount Pinatubo in 1991 is an $M = 6.5$ event, where $M = \log[m] - 7$ and m is the erupted mass in kilograms. Figure 11.2 shows a generalised magnitude versus return period relationship for explosive eruptions based on the studies of Mason *et al*. (2004) and Deligne *et al*. (2010). Intensity is a very useful indicator of the violence of an eruption and is measured in kilograms of magma

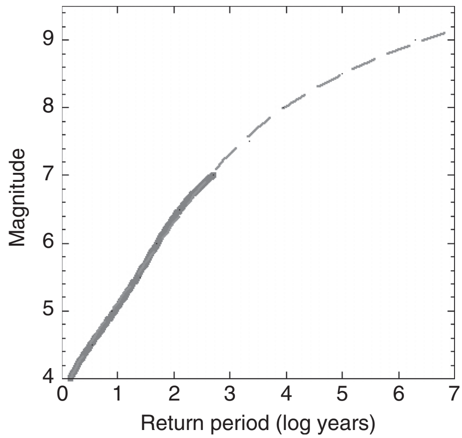

Figure 11.2 Global magnitude versus return period for explosive eruptions of magnitude 4 and greater from the analysis of Deligne *et al.* (2010) (solid curve) and an extrapolation (dashed curve) based on an upper threshold of $M = 9.3$ for the Earth and the analysis of Mason *et al.* (2004) of eruptions with $M > 8$.

erupted per second. Since intensity commonly fluctuates greatly during many eruptions, peak intensity is often a useful parameter to estimate. The volcanic explosivity index (VEI) introduced by Newhall and Self (1982) is widely used as a metric of eruption scale. The VEI (Figure 11.3) is assigned according to both quantitative estimates of volume and intensity and more qualitative indicators. Durations can range from less than a day, sometimes with extreme intensity (5 km^3 of magma erupted from Mount Pinatubo on 15 June 1991), to persistently active volcanoes that erupt almost continuously with many small eruptions (Stromboli volcano in Italy has been erupting since Roman times or before). Rare extreme eruptions ($M > 8$, i.e. up to 300 times the magnitude of Pinatubo) are the only natural phenomena apart from meteor impact that can have a worldwide impact through global effects and consequent extreme short-term climate change, sometimes described as volcanic winter, when cooling of several degrees may last for several years (Robock, 2000).

The main hazardous phenomena are now summarised. A very good source of up-to-date information on volcanic hazards and volcanoes is the US Geological Survey (http://volcanoes.usgs.gov/). More detailed accounts of volcanic processes and hazards can be found in Blong (1984), Tilling (1989) and Sparks *et al.* (1997).

Explosive eruptions are the most important primary volcanic hazard. There are two basic phenomena (Figure 11.4). First, explosive eruptions form high volcanic plumes in the atmosphere (Figure 11.4a), which disperse volcanic fragments ranging in size from a few metres to dust. Much of these ejecta are centimetres to millimetres to a few tens of microns in size and are collectively known both as tephra and as pyroclastic particles. Volcanic ash is defined as particles of less than 4 mm across. Volcanic plumes range from a few kilometres to a few tens of kilometres in height (Sparks *et al.*, 1997) and are dispersed by wind patterns (Figure 11.5a). Particles fall out of the plume to form accumulations on the ground known as

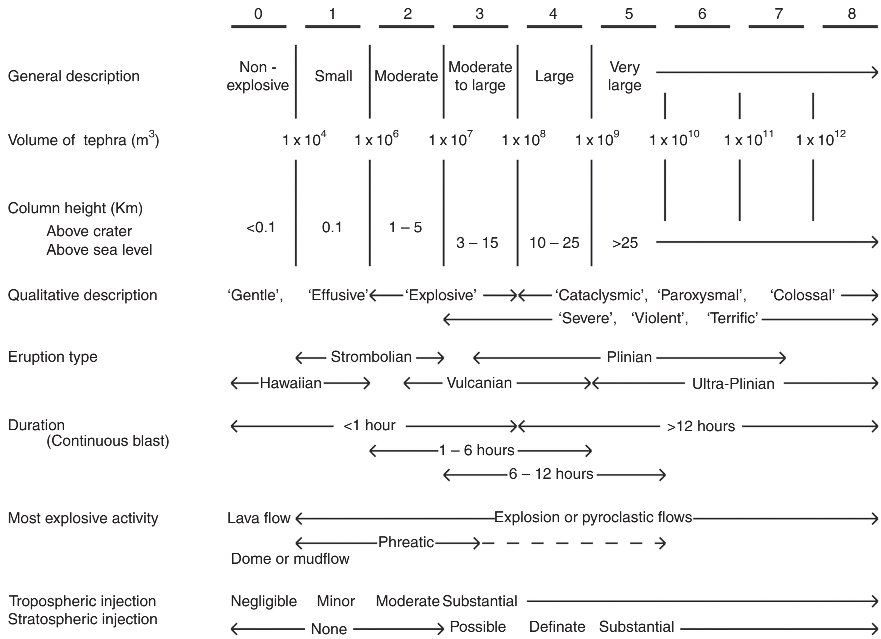

Figure 11.3 Description of the volcanic explosivity index (VEI), after Newhall and Self (1982).

tephra fall deposits. Near the volcano, typically within a few kilometres, large ejecta, commonly known as ballistics, can break roofs and cause fires, and fragments larger than 10 cm are likely to cause death or serious injury (Baxter, 1990). Tephra fall deposits that are sufficiently thick can cause roofs to collapse and death or injury to those inside (Blong, 1984; Spence *et al.*, 2005). Volcanic ash can have major environmental impacts (Durant *et al.*, 2010). Tephra commonly carries toxic chemical components and acids such as H_2SO_4 (sulphuric acid), metals and fluorine. Ash can prevent photosynthesis so cause crop failure, poison livestock, pollute water supplies and cause health hazards such as dental and skeletal fluorosis. Thus areas affected by tephra fall can threaten food security, and famines have followed a number of very large eruptions. For example, about one-third of the population of Iceland died due to the famine caused by the Laki volcano eruption in 1783, and there were severe environmental and health effects in Europe (Grattan and Charman, 1994). Very fine ash is a health hazard (Baxter, 1990; Hansell *et al.*, 2006) and can compromise the operation of technological facilities such as nuclear power stations and electrical infrastructure (Bebbington *et al.*, 2008) and aircraft, as widely experienced in Europe during April and May 2010 as a result of the eruption of the Eyjafjallajökull volcano in Iceland.

Second, explosive eruptions can generate hot, rapidly moving turbulent flows of lava fragments and ash (known as pyroclastic flows) by a phenomenon called column collapse (Figures 11.4b and 11.5b), where the erupted mixture is too dense to keep rising and collapses from height above the vent. Such pyroclastic flows can spread across terrain at

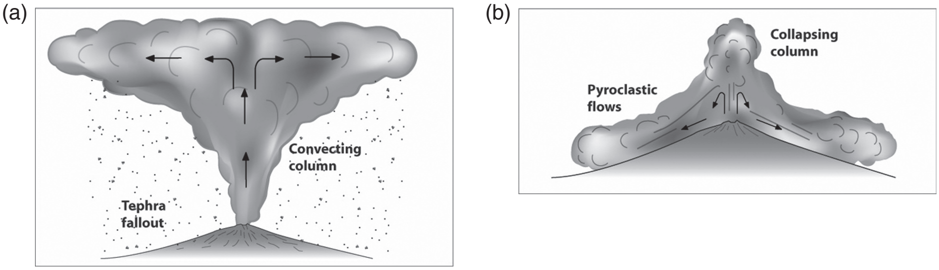

Figure 11.4 (a) Schematic diagram to illustrate the structure and dynamics of a convection eruption column with tephra fallout. Here an intense explosive discharge of pyroclastic ejecta and gas at the vent mixes with the atmosphere to form a buoyant column in the atmosphere, which then spreads out laterally around a height of neutral buoyancy to form an umbrella cloud. Tephra (volcanic fragments of all sizes) fall out of the column. (b) Schematic diagram to show the formation of pyroclastic flows during explosive eruptions. Here the intense vertical discharge of volcanic ejecta and gas mixes with the atmosphere but runs out of kinetic energy while still denser than the surrounding air. The column collapses as a fountain around the vent and forms flows of hot pyroclastic particles.

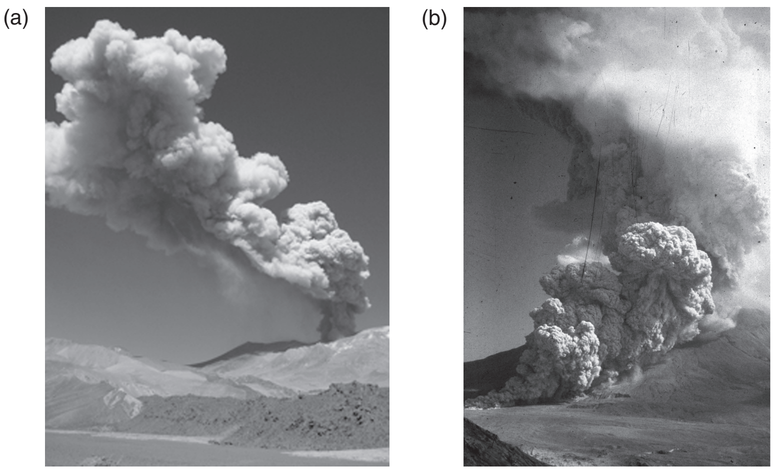

Figure 11.5 (a) Small volcanic plume generated by explosive eruption at Lascar volcano, Chile showing the effects of the wind as the plume levels out at the height of neutral buoyancy. (b) Pyroclastic flow formed by column collapse during the 1980 eruption of Mount St Helens (photograph from US Geological Survey).

speeds of tens to hundreds of kilometres per hour, at temperatures of several hundred degrees. Nothing in their path can survive and they are historically a major killer (Baxter, 1990). Almost the entire population of St Pierre (29 000) in Martinique was killed by a laterally directed explosion, essentially a particularly energetic variety of pyroclastic flow (Figure 11.6).

Figure 11.6 Destruction in the town of St Pierre in Martinique (8 May 1902) from a violent pyroclastic flow or volcanic blast from Mont Pelée volcano.

Very viscous lavas form unstable domes that can accumulate on a volcano and then generate dome collapse pyroclastic flows or high-speed lateral explosions when the lava dome reaches a critical internal pressure. Dome collapse pyroclastic flows can be very energetic and destructive. A recent example was the death of 20 people on Montserrat due to a collapse of the andesite lava dome at the Soufrière Hills volcano on 25 June 1997 (Loughlin *et al.*, 2002a). Pyroclastic flows vary greatly in scale and intensity. Most of them share the characteristic of having a dense concentrated basal flow and an overriding dilute hot and turbulent cloud of fine ash that usually extends to greater heights. This upper part, sometimes described as a surge, can spill out of valleys and move into unexpected areas. This dual character of the flow has led in the recent past to tragedy. In 1991 a pyroclastic flow formed by the collapse of a lava flow at Mount Unzen, Japan, moved down a deep valley on the volcano's flanks (Ui *et al.*, 1999). Forty-three people situated on a ridge well above the valley were killed by the dilute surge cloud.

Lava flows, while usually not life-threatening, can also be very destructive, bulldozing and burying whole villages and sometimes setting towns on fire. The town of Catania in Sicily was destroyed by lava in 1699. A recent example is the January 2002 eruption of Nyiragongo volcano in the Democratic Republic of Congo, where lava destroyed 15% of the town and caused fires with many burn injuries (Komorowski *et al.*, 2003). An explosion of a gas station overrun by lava led to over 470 people with burns and gas intoxication. Viscous lava domes are very hazardous due to their potential to generate pyroclastic flows, as described above.

There are a number of secondary hazards associated with eruptions that are also highly destructive. Volcanic edifices are often unconsolidated and fractured, and potentially unstable, so landslides are common. Large volcanic landslides, known as debris avalanches, may involve collapse of a large proportion of the volcanic edifice forming an avalanche that can travel tens of kilometres in more extreme events. Such large slope failures can be triggered by an eruption when magma is intruded into the edifice and the collapse can also trigger a very violent lateral explosion. This happened at Mount St Helens on 18 May 1980, with the blast devastating 600 km^2 in four minutes (Voight *et al.*, 1981). There were only 57 fatalities because there was an exclusion zone and the eruption took place early on a Sunday morning, when loggers were not working and hikers were few in number. A variety of causes have been identified as triggers for major slope failure on volcanoes. These include loading of the edifice by growth of lava domes; rise in pore pressure due to fluid movement perhaps activated by magma rise and related unrest; earthquakes; and intense rainfall. In the latter two cases the collapse may be unrelated to volcanic processes. For volcanoes in or close to the sea or lakes, tsunamis are a major hazard. About 15 000 people were killed by the tsunami caused by a debris avalanche due to the collapse of a lava dome at Mount Unzen, Japan, in 1792.

Another major volcanic hazard is flows of volcanic debris and water, known as lahars (an Indonesian word). The most important factor is heavy rain, which can remobilise large amounts of loose debris generated by eruptions. A good example is the generation of lahars after the 1991 eruption of Mount Pinatubo. In this case the valleys cutting the flanks of the volcano were choked with huge amounts of unconsolidated and easily eroded deposits generated by pyroclastic flows during the eruption. For almost two decades since the eruption lahars have been episodically generated around Pinatubo by intense tropical rainstorms (van Westen and Daag, 2005) and associated fatalities are estimated to be about 700. Another common mechanism is where pyroclastic flows enter into water bodies, such as a river, and then transform to a lahar. Lahars can also be generated by rapid melting of ice. In 1985, 25 000 people were killed in the town of Armero, Colombia, when an explosive eruption of Nevado del Ruiz melted the icecap on the volcano to form lahars, which buried the town 70 km away (Voight, 1990). In some cases lahars are generated by muddy water being directly extruded from the ground, likely as a consequence of disturbance of the groundwater systems by magma ascent (Sparks, 2003). Mudslides can be generated by intense rainfall on dormant volcanic edifices, a good example being Casita volcano, Nicaragua, in 1998 due to the passage of Hurricane Mitch (Kerle *et al.*, 2003).

Other hazards associated with volcanoes can include lightning due to charge generation and separation of particles in the plume (Mather and Harrison, 2006), fire caused by hot ejecta (and lightning); shockwaves caused by powerful explosions (e.g. damage to buildings 3 km from Kirishima volcano, Japan, February 2011); pollution of water supplies and the poisoning and asphyxiating effects of gases. Of current interest is the hazard to aviation of suspended fine ash in the atmosphere.

The diversity and, in many cases, strong interdependencies of these various hazards poses special problems for risk assessment. The different kinds of phenomena can occur simultaneously, or one may follow from another. For example a pyroclastic flow eruption or heavy ash fall leads to conditions favourable to lahar generation. The hazards footprint can also be very different between the hazards, making the preparation and presentation of hazard zoning maps quite complicated.

11.3 Forecasting, prediction and early warning

Volcanic eruptions occur when magma rises to the earth's surface. The ascent and underground movement of magma and associated geothermal fluids gives rise to several precursory phenomena, such as numerous small earthquakes, ground deformation, heating of groundwater, chemical changes in springs and fumaroles and release of volcanic gases at the surface in advance of the magma (Figure 11.7). Such phenomena may be detected prior to an eruption to allow early warnings to be given. Likewise, geophysical and geochemical data generated by monitoring support the management of volcanic crises as they unfold.

The technology to monitor volcanoes is improving rapidly, as is the ability to deal with large amounts of data using the ever-increasing power and speed of computers. For those volcanoes that are well monitored there have been some notable successes in forecasting (Sparks, 2003). Although precise prediction is rarely possible, there are now examples of volcanic eruptions where the assessment of precursory signals made it possible for the scientific teams to recognise that the volcano was in a dangerous or critical state, leading to timely evacuation based on this advice. The best example of a successful evacuation is the case of the 1991 eruption of Mount Pinatubo (Newhall and Punongbayan, 1996b), where as many as 20 000 lives were likely saved. As well as the technological advances, the skill of experienced volcanologists and their appreciation of the power of eruptions are critical to effective early warning and crisis management because large amounts of diverse data and information have to be integrated together within the framework of conceptual understanding of volcanic processes.

Current improvements in volcano forecasting and early warning are largely driven by technology linked into improved understanding of the physics of volcanic processes and advances in data-led conceptual models of volcanic systems and processes (Sparks, 2003; Sparks and Aspinall, 2004). Monitoring of volcanic earthquakes by seismic networks remains the most tried and trusted approach for almost all active volcanoes (McNutt, 2005). Magma and fluid movements typically cause myriad small earthquakes and their detailed examination can allow distinctions to be made between various kinds of subterranean phenomena and increasingly quite well-defined identification of the magma conduits, fluid pathways and fracture systems that are activated during volcanic unrest and eruption. The dimensions, shapes of fractures, imposed external stress systems and internal pressures can be inferred from seismic observations. Small earthquakes related to breaking rock in shear can be distinguished from movement of fluids and gases along fractures. Volcano seismologists are getting better at distinguishing source and pathway effects. Over the last decade or more the widespread deployment of broadband three-component seismometers, which detect motions over a wide frequency range in three dimensions, has revolutionised the ability to assess the processes acting on and the state of stress in volcanic systems.

Ground deformation accompanies most eruptions and their precursory events (Dzurisin, 2003), and these movements reflect fluctuations in pressure of magma and fluid bodies in the crust. Such movements can be detected by several different complementary techniques,

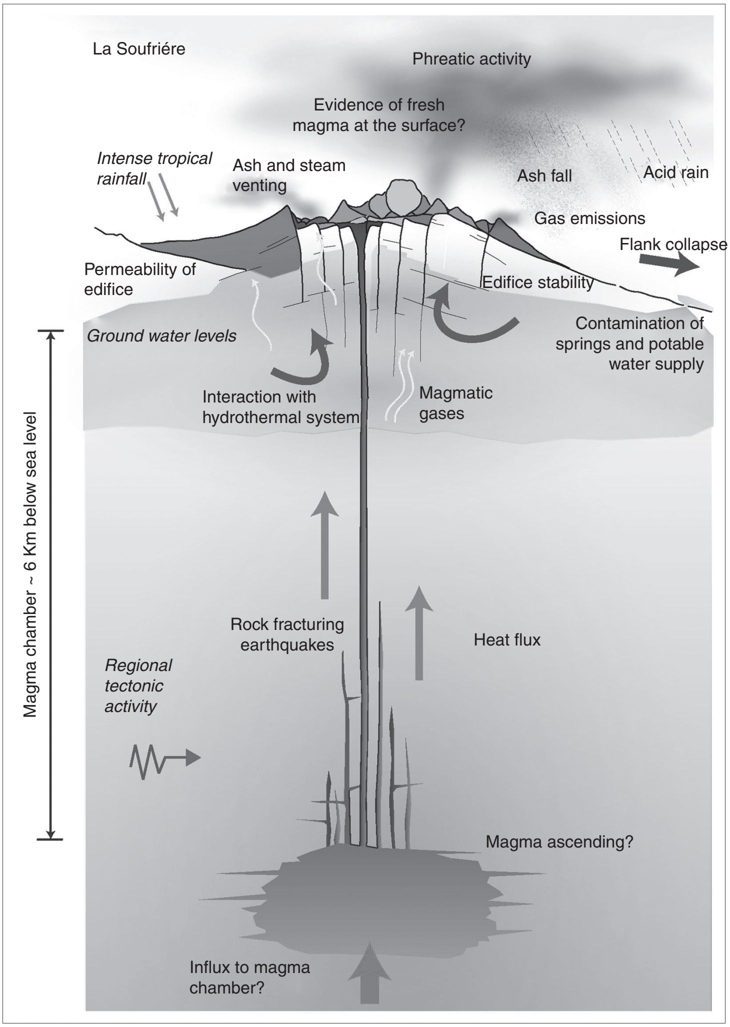

Figure 11.7 Schematic diagram depicting the main effects of magma rising up a conduit to supply an eruption.

including precise levelling, electronic distance measurement (EDM), tilt meters, GPS, synthetic aperture radar interferometry (inSAR) and borehole strain meters. Mass changes can also be detected by gravity measurements. InSAR has become particularly important (Burgmann *et al*., 2000) in detecting volcano state changes in remote parts of the world (e.g. Pritchard and Simons, 2004). The recent introduction of L-band (25 cm wavelength) devices is enabling useful data to be retrieved from areas where vegetation has previously been a problem. These change detection methods act as indicators of pressure variations in volcanic systems. The interpretation of ground deformation models has been dominated by application of the Mogi model (Mogi, 1958), which is a quantitative analysis of surface deformation due to a single-point pressure source embedded in an elastic half-space. Recently advances in numerical models of ground deformation have been developed, using finite element modelling (FEM) for example. FEM models allow variations of elastic rock properties, viscoelastic rheologies, geological layering, surface topography and more complex chamber geometries to be considered (e.g. Hautmann *et al*., 2010).

There have been major advances in gas geochemistry (Burton *et al*., 2007; Edmonds, 2008). Gas monitoring using ground-based and satellite remote-sensing technologies augment, and to some extent supersede, the direct (and often dangerous) sampling of volcanic fumaroles. Traditional methods of measuring the temperature of volcanoes and volcanic features, such as crater lakes, have been augmented by thermal sensors on satellites. Remote monitoring of volcanic gases has been facilitated by miniaturisation and reduced costs of instrumentation and increases in computing power. Spectroscopic measurement of SO_2 emission rate has increased in sampling frequency from one measurement per day, 20 years ago, to one measurement per minute with mini UV spectrometers today (e.g. Galle *et al*., 2003). Modern UV cameras boast sampling frequencies approaching one per second, allowing direct comparison with other rapid-sampling geophysical techniques (e.g. Dalton *et al*., 2010). Furthermore, contemporary earth observation satellites provide a suite of potential sensors for observing volcanic degassing (Thomas and Watson, 2010), at both UV (e.g. Carn *et al*., 2008) and IR (e.g. Thomas *et al*., 2009) wavelengths. Instrumental advances are also being made in monitoring of CO_2 from volcanoes using airborne platforms (e.g. Werner *et al*., 2000, 2006). Soil gas emanations can also be precursory indicators of eruptions (e.g. Baubron *et al*., 1991).

Recent progress in forecasting and predicting eruptions has been discussed by Sparks (2003), Sparks and Aspinall (2004) and McNutt (2005); the general situation has not changed much since then, although there continue to be technological and modelling advances which add to scientific capability (Sparks *et al*., 2012). In general, precise prediction is not achievable, an exception being the remarkable prediction of the 2000 eruption of Mount Hekla using strain meter data (Sparks, 2003), based on the work of Linde *et al*. (1993). In most cases, early warning is achieved in situations where the responsible experts in an observatory make a judgement call, taking account of all the scientific evidence and the associated uncertainties. Sometimes these judgements have to be made rapidly because the build up from low background activity, with little cause for concern, to a significant eruption can be as short as a few tens of minutes.

There are permanent observatories on many active volcanoes dedicated first to recognising the signals of an impending eruption and then to monitoring eruptions. Worldwide there are 80 such observatories (the World Organisation of Volcano Observatories, or WOVO; http://www.wovo.org/) and also regional networks of seismometers and ground deformation measurements (such as GPS). However, many of the world's volcanoes remain unmonitored with little or no baseline information. Major volcanic crises in the developing world have often necessitated calls on outside scientific assistance. The Volcano Disaster Assistance

Programme (VDAP) of the US Geological Survey has played a particularly prominent role in responding to such emergencies (http://volcanoes.usgs.gov/vhp/vdap.php).

Signals precursory to volcanic eruptions take place on a wide range of timescales, from many years to a few tens of minutes (Sparks, 2003). Precise prediction about the onset time of an eruption is rarely possible, but there are many examples where eruptions have been successfully forecast hours, days or weeks ahead of the actual event. A major problem is that active volcanoes often show unrest, such as earthquakes, ground deformation, gas release and steam explosions, but this unrest does not always lead to eruption. Indeed, there are many more cases of periods of unrest without subsequent eruptions than there are eruptions (Newhall and Dzurisin, 1988; Biggs *et al*., 2009; Poland, 2010; Moran *et al*., 2011). Volcanic unrest may come about because of movement of fluids underground, tectonic processes and the intrusion of magma at depth or a combination of these factors. Failed eruptions can lead to so-called ‘false alarms’, although these are better termed unfulfilled alarms (the cause for alarm is usually real enough!). Thus, when there is volcanic unrest above background levels, the outcome is highly uncertain.

The difficulty of interpreting volcanic unrest and predicting eruptions has serious consequences for risk assessment and crisis management. One example is the Soufrière Hills volcano, Montserrat, where periods of unrest without eruption occurred in 1896–1897, 1933–1937 and 1966–1967. When new unrest began in 1992, people on Montserrat were not anticipating that an eruption would follow, so were ill-prepared when a major eruption started in July 1995 (Robertson *et al*., 2000). Another example is that of Miyakejima volcano, Japan, where over 90% of shallow dyke intrusions that take place do not connect to the surface as eruptions (Geshi *et al*., 2010). Evacuations are quite commonly called during periods of strong volcanic unrest, exemplified by the evacuation of the town of Basse Terre on Guadeloupe in 1976 (Feuillard *et al*., 1983; Fiske, 1984; Section 11.5.2). One of the consequences of so-called false alarms is that populations may perceive that an evacuation is called unnecessarily, with loss of trust in the scientists and a reluctance to respond when another period of unrest starts.

Once an eruption has started there continue to be great challenges in judging the course of the eruption. It is typically very difficult to forecast the exact style, size and duration of eruptive activity, and volcanologists are always faced with significant uncertainties that have to be communicated to decision-makers. For volcanoes like Vesuvius, which are close to large populations, evacuation plans are typically based as much on logistics as they are on the ability of scientists to make reliable forecasts of an eruption. In the case of Naples, the evolving evacuation plan still assumes there will be several days of advance warning, but many in the scientific community are sceptical that a confident and reliable forecast that an eruption is likely to take place can be given on that timescale. Likewise, evacuations can create major problems when there have been unfulfilled alarms. Managing the realities of the large uncertainties in forecasting and giving reliable early warnings, and matching these realities to the requirements of decision-makers and expectations of the public, are very common challenges in volcano crisis management.

11.4 Hazard and risk assessment

The classical basis for forecasting the nature of a future eruption is the historical record or geological studies of past eruptions. Since the 1970s the primary communication tool in applied volcanology has been the hazards map. A typical study involves charting out young volcanic deposits to generate maps for each type of hazard, reflecting areas that have been affected by past volcanic events. Tilling (1989) provides a comprehensive account of this classical approach. Increasingly, such studies are augmented by modelling of the processes involved. Here, models are run under the range of conditions thought to be plausible for the particular volcano and commonly calibrated to observed deposit distributions. Examples of modelling investigations for the Soufrière Hills volcano, Montserrat include distribution of pyroclastic flows (Wadge, 2009) and probabilistic distribution of ash fall deposits (Bonadonna *et al.*, 2002). Mapping is complemented by chrono-lithostratigraphic studies that seek to characterise the frequency of eruptions of different size and diagnose the eruption style.

Typically the outcome of such geological studies is a zonation map. The area around a volcano is typically divided into zones of decreasing hazard that are used to identify communities at high risk, to help in the management of volcanic crises and for planning purposes by the authorities. A very common type of map will have a red zone of high hazard, orange or yellow zones of intermediate hazard (often both), and a green zone of low hazard. Implicitly, such maps also depict the risk to people occupying a zone. Boundaries between zones are typically marked initially by lines on maps based on judgement by scientists about hazard levels. The precise positioning of such boundaries in published versions of these maps, however, may be modified to take account of administrative issues and practical matters, such as evacuation routes, as determined by civilian or political authorities. Figure 11.8 shows the 2010 hazard map for the Soufrière Hills volcano, Montserrat (http://www.mvo.ms/). Here the hazard map is linked to a hazard-level scheme that depends on the activity of the volcano. The map zones change their status in terms of hazard level as the activity of the volcano changes. As the hazard level of each zone changes, restrictions on the allowed activities are increased or decreased and actions by administrative authorities specified for each zone are changed.

The position of hazard zone boundaries is implicitly probabilistic, but it is only recently that more rigorous approaches to locating such boundaries have been developed. Hazard and derivative risk maps of volcanoes are produced by a variety of organisations. Geological surveys or government institutions typically have official responsibility for providing scientific information and advice to civilian, political or military authorities, who have the responsibility to make policy or decisions such as whether to evacuate. Academic groups and insurance companies also generate maps, so there is the opportunity for serious, and unhelpful, contention if any of these do not appear to agree with hazard or risk maps from an official source.

For disaster mitigation purposes, volcanic risk is usually defined in terms of loss of life and the main strategy in most volcanic crises is to move people out of harm's way by evacuation. It is useful in this context to distinguish between exposure and vulnerability in calculating risk. An exposed population may be living in normal circumstances in an area that has potentially high

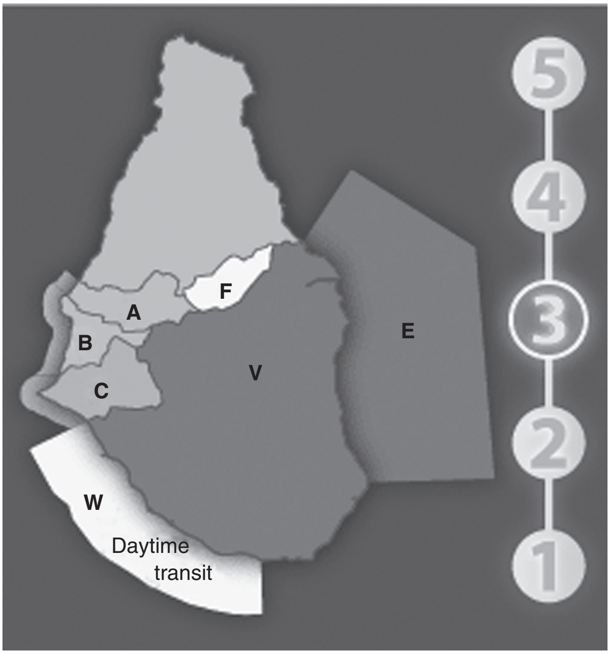

Figure 11.8 A hazard map for Soufrière Hills volcano, Montserrat at alert level 3. The letters on the map designate regions which are colour coded to imply their status in terms of access. For example, area A is the red exclusion zone under alert level 3.

hazard when the volcano becomes active. Their risk will not only depend on their exposure but on their vulnerability, which is dependent on many physical, economic, cultural and social factors (see Chapter 16), as well as the existence of a well-thought-out plan for evacuation.

In periods of dormancy or low activity, reduction of risk can be promulgated through land-use planning, evacuation planning and raising awareness of the hazards and attendant risks in potentially affected communities. However, in many parts of the world the application of hazard and risk assessment to preparedness, resilience and mitigation is limited. Volcanic risk should also be defined in terms of economic loss or potential destruction of key facilities. Such analysis can be a useful guide to inform urban planning and location of major technological facilities such as oil refineries, large dams and nuclear power stations. Damage to critical infrastructure could impact a large number of people and their economy long after an eruption. The only arena where such hazard and risk assessments have been developed substantially is in connection with the possible locating of sites for radioactive waste repositories (Connor *et al*., 2009). In a related context, the International Atomic Energy Authority (IAEA) will be publishing guidelines in 2011 for volcanic hazards and risk assessment for nuclear installations (Hill *et al*., 2012).

In the last 15 years or so, there has been a strong move to develop more robust and structured approaches to volcanic hazard and risk assessment and the related task of volcano crisis management. The methods being developed have much in common with those being developed for other natural hazards. For example, ash fall hazards and risks are increasingly assessed by eruption column models, atmospheric advection-diffusion transport models and statistical information on the atmospheric wind systems (e.g. Bonadonna *et al.*, 2002; Costa *et al.*, 2006, 2009). Validation and calibration is done by comparison with observations, but systematic comparison between the models themselves has not yet been fully developed. There is a range of models including sophisticated numerical physics-based models of volcanic flows (e.g. Todesco *et al.*, 2002; Charbonnier and Gertisser, 2009), ensemble approaches using Monte Carlo techniques (e.g. Hincks *et al.*, 2006) and empirical simplified models such as PYROFLOW (Wadge, 2009) or PFz (Widiwijayanti, 2009). So far, the more sophisticated models are largely research tools and the community has not reached accord as to the extent to which these models should be applied in hazards assessments and risk analysis. One argument is that they are the best we have got and so they should be used, while others see them as too deficient in terms of understanding the underlying physics so they could be misleading. To a large extent it is the empirical simplified models that are most widely used in hazards assessments. An example of such models is the TITAN code developed at the State University of New York at Buffalo in the United States for granular avalanches, and which is now being widely applied to pyroclastic flow hazards (e.g. Saucedo *et al.*, 2005; Charbonnier and Gertisser, 2009). LAHARZ (Schilling, 1998; Schneider *et al.*, 2008) is an example of an automated and highly empirical model of lahar inundation widely used for hazard assessment. The model parameters have been calibrated by 27 lahars from nine different volcanoes (Iverson *et al.*, 1998).

Thus, it is only in the last decade or so that risk and uncertainty analyses have entered into common discourse in volcanology. Logic and event trees, with associated analysis of uncertainties, have been introduced (Newhall and Hoblitt, 2002; Marzocchi *et al.*, 2004). The event tree has been used extensively, particularly by the USGS VDAP team, in several volcanic emergencies (C. Newhall, pers. comm.), but there are only a few examples of published descriptions of the application of the methodology, including Pinatubo (Punongbayan *et al.*, 1996) and Montserrat (Sparks and Aspinall, 2004). The Bayesian event tree (BET) model is a flexible tool to provide eruption forecast and volcanic hazard and risk assessment (the INGV code can be downloaded free at http://bet.bo.ingv.it/). The BET is a graphical representation of events in which individual branches are alternative steps from a general prior event, state or condition, through increasingly specific subsequent events (intermediate outcomes) to final outcomes. Such a scheme shows all relevant possible outcomes of volcanic unrest at progressively higher degrees of detail. The probability of each outcome is obtained by combining opportunely the probabilities at each node of the tree. The Bayesian approach applied to the event or logic tree brings two key advantages. First, the probabilities at the nodes are described by distributions, instead of by single values; this allows appropriate estimates of the uncertainty related to the probability evaluations to be incorporated into the calculations formally. Second, the Bayesian approach makes easier the merging of all the relevant available information such as theoretical models, prior beliefs, monitoring measures and past data.

The BET model has been formulated in different ways, depending on intended use. The application to eruption forecasting, BET_EF (Marzocchi *et al.*, 2008), is focused on the first part of the event tree, i.e. from the onset of the unrest up to eruption occurrence of a specific size. The input data are mostly monitoring measures; depending on what the monitoring observations indicate and how they change, BET_EF updates the evaluation of an eruption forecast in near real time. The primary purpose of this code is to assist decision-makers in managing a phase of unrest. The code has been set up for different volcanoes and used in two recent experiments that simulate the reactivation of Vesuvius (MESIMEX experiment: Marzocchi and Woo, 2007; Marzocchi *et al.*, 2008) and the Auckland Volcanic Field (Ruaumoko: Lindsay *et al.*, 2010). It has also been applied retrospectively to the pre-eruptive phases of the 1631 eruption of Vesuvius by using the information reported in contemporary chronicles (Sandri *et al.*, 2009).

The BET_VH model can be applied for long-term volcanic hazard estimation (Marzocchi *et al.*, 2010), focusing on the impact of different hazardous phenomena in areas surrounding the subject volcano. As inputs, BET_VH incorporates results from numerical models simulating the impact of hazardous volcanic phenomena area by area, and data from the eruptive history of the volcano of concern. For output, the code provides a wide and exhaustive set of spatio-temporal probabilities of different events. This version of the BET code has been used in a recent application to long-term tephra fallout hazard assessment at Campi Flegrei, Italy (Selva *et al.*, 2010).

However, such sophisticated probabilistic hazard assessments, with expressions of scientific uncertainty embedded, pose a significant challenge for decision-makers to digest, since they have to take decisions under their own constraints, which are mostly non-scientific. A rational use of the probabilistic BET model, or any probabilistic assessment model in general, requires the definition of a volcanic risk metric (VRM). Marzocchi and Woo (2009) propose a strategy based on coupling probabilistic volcanic hazard assessment and eruption forecasting with cost–benefit analysis via the VRM concept. This strategy, then, has the potential to rationalise decision-making across a broad spectrum of volcanological questions. When should the call for evacuation be made? What early preparations should be made for a volcano crisis? Is it worthwhile waiting longer? What areas should be covered by an emergency plan? During unrest, what areas of a large volcanic field or caldera should be evacuated, and when? The VRM strategy has the paramount advantage of providing a set of quantitative and transparent rules that can be established well in advance of a crisis, optimising and clarifying decision-making procedures and responsibilities. It enables volcanologists to apply all their scientific knowledge and observational information to assist authorities in quantifying the positive and negative risk implications of any decision.

The eruption of the Soufrière Hills volcano, Montserrat, was the first time that structured expert elicitation techniques have been applied in a real crisis (Aspinall and Cooke, 1998; Sparks and Aspinall, 2004). During a volcanic eruption the approach is to identify all the possible outcomes over some practical risk management time period, such as a year or a few weeks. Various outcomes may be benign or lethal, volcanic risk so far being almost exclusively defined in such situations in terms of the annualised probability for loss of life, there being little that can be done to mitigate property damage on an immediate basis.

Typically, any particular hazard is represented in this structured approach by an interlinked series of disaggregated events or processes. Commonly, the ultimate risk level depends on conditional probabilities in the chain of events that lead to risk. As an example, the size and likelihood of a dome collapse pyroclastic flow at the Soufrière Hills volcano depends on the volume of the dome, its direction of growth and the rate of growth, and can be modulated by the occurrence of intense rainfall that promotes destabilisation of the dome. The chance of a pyroclastic flow reaching a particular place, such as a village, depends on the initial volume and momentum of the flow, the rheological properties of the flow and topography. Some, such as dome volume, may be accurately known. Others, like the long-term occurrence of intense rainfall events, may require regional data that are treated statistically. Yet others may require an empirical model (e.g. PYROFLOW: Wadge, 2009) based, for example, on observed runouts of pyroclastic flows of different volumes or laboratory data on rheology. All of these components have epistemic and aleatory uncertainties. Where data are scarce or understanding of the processes is poor, expert judgement can be used. To go from hazard to risk requires additional information on vulnerability and exposure, adding further complexity and uncertainty. Variation in vulnerability can be modelled statistically; for example, by applying Monte Carlo re-sampling methods the overall risk level can be evaluated using different population distributions to show how risk can be mitigated by relocating groups of people away from the hazards.

In line with this thinking, during the eruption of the Soufrière Hills volcano in Montserrat, a scientific advisory committee (SAC) has met approximately every six months since 1997, applying the methods described above. The eruption is still ongoing at the time of going to press (September 2012) and the SAC remains operational. The SAC typically consists of several scientists representing a range of expertise, and interfaces with staff from the Montserrat Volcano Observatory (MVO), who are responsible for the day-to-day monitoring, hazard assessment and provision of advice to the government authorities. The SAC looks at the long-term trends and outlook for the volcano to facilitate planning and management. A period of six months was chosen by the SAC as a benchmark, but both longer and shorter periods have been considered, depending on circumstances. Occasionally the SAC has convened at short notice to support the MVO and provide advice in periods of elevated activity, when evacuations may be necessary.

Figures 11.9, 11.10 and 11.11 show examples of some key products of these formal hazard and risk assessments. The event tree (Figure 11.9) shows an example of a range of potential future hazardous events in a dome-building eruption, with branches that depict alternative outcomes. Probabilities and uncertainties in these probabilities are assessed for each branch on the tree through integration of all pertinent evidence and models using expert elicitation. Such event trees develop and grow as an eruption proceeds; the skills of the science team can be assessed by comparing the actual outcome with the events that are assessed to be most likely. Curves of societal risk in Figure 11.10 consist of plotting the probability of a certain number of casualties being exceeded versus the number of casualties. Each curve is based on a certain assumed distribution of population and, to be cautious, also assumes there is no warning. In the case of Montserrat, the island was divided into several

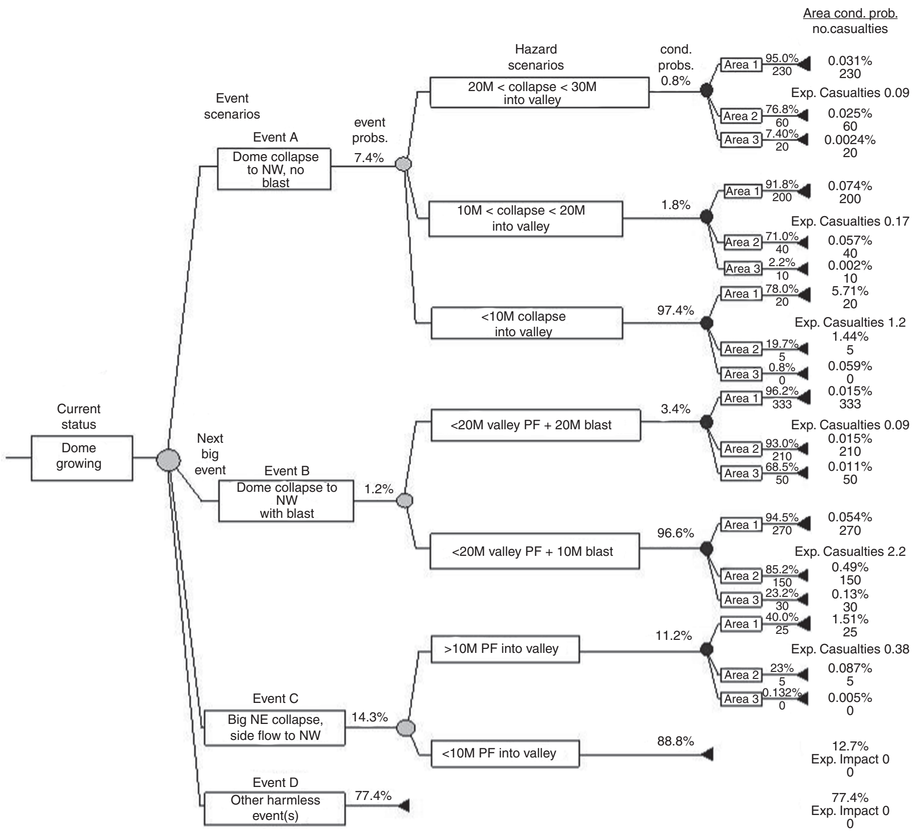

Figure 11.9 A simplified event tree for four pyroclastic flow and blast event scenarios in a dome-building eruption, and potential casualty risks in three populated areas (based on a typical case for the Belham Valley and Soufrière Hills volcano, Montserrat). Event D denotes any eruption scenario that does not impact the Belham Valley and therefore presents no risk to residents there; events A, B and C are three different ways in which a dangerous flow or blast could impact the valley and adjacent areas. The hazard scenarios are rudimentary classifications, scaled by volume(s) of material involved – e.g. '20M' means 20 million cubic metres of lava. Branching probabilities are usually obtained by elicitation; potential numbers of casualties are based on global experience and are functions of the total number of people in each area and the nature of the hazard. In a quantitative risk analysis based on such an event tree, all values would be characterised by appropriate statistical distribution to represent uncertainties. For most eruption situations, a comprehensive risk tree like this can easily extend to hundreds or thousands of branches. Expected casualties indicate the statistical values for the particular scenario. These expectation values show it is the higher probability/less intense events that provide the greatest risks, because the more extreme events may kill more but have much lower probabilities proportionately.

areas, with population estimates for each zone. If people are evacuated from a high-risk area then the risk curve moves downwards. Decision-makers can then see the reduction in risk due to selective timely evacuation. Such curves can also be used to monitor how volcanic risk varies due to fluctuations in the scientists' appraisals of volcanic activity, as well as

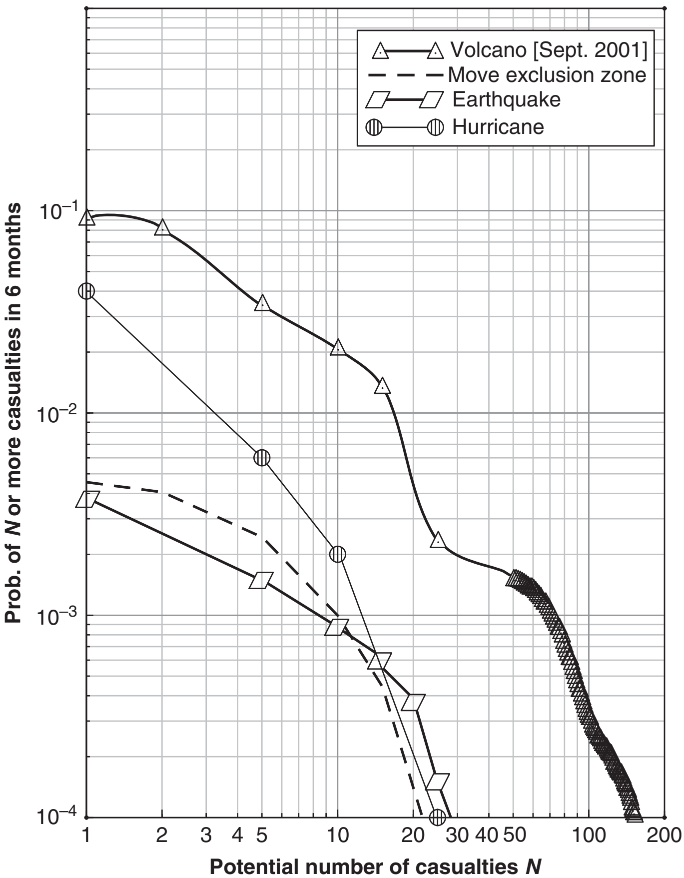

Figure 11.10 Example of probability curves for societal risk in Montserrat. Each curve shows the probability plotted against number of casualties over a six-month period, and is the mean of thousands of simulations using Monte Carlo re-sampling from uncertainty distributions on the parameters that influence risk. The upper curve (solid line) is the exposure within the Belham Valley area populated before the evacuation, and the lower curve (dashed line) shows the reduction in risk with evacuation. Regional risk curves for hurricanes and tectonic earthquakes are shown for comparison. Note that for each curve uncertainties at the 5% and 95% levels were calculated but for clarity are not shown.

compare the volcanic risk with the risk from other familiar hazards such as hurricanes and earthquakes.

While Figure 11.10 shows overall societal risk levels for the whole population, usually there are also concerns about levels of exposure to the volcano for individuals, and what is acceptable or tolerable in this context. In health and safety terms, this measure of risk is commonly expressed as the individual risk per annum (IRPA) of death and, in the case of Montserrat, a typical individual risk ladder is shown in Figure 11.11. The ladder shows a resident's relative risk exposure due to the proximity of the volcano when living full-time in

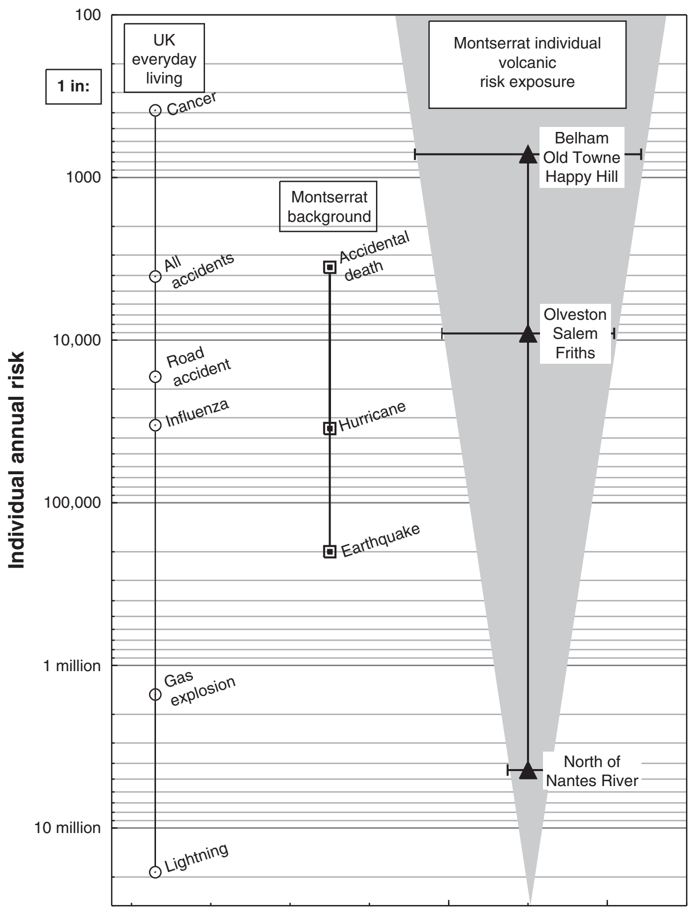

Figure 11.11 Example of an individual risk ladder for Montserrat residents living near the Belham Valley, showing an individual's volcanic risk exposure as a function of locality in March 2010 (right-hand ordinate). The adjoining ladders on the chart show: background risk levels for an individual from natural hazards on island and accidental death (excluding road accidents) and some everyday living risks for the UK (adapted from SAC 14 Report – available on the MVO website).

certain areas. One of the main purposes of such a chart is to help convey and communicate the extent of any additional risk from living on the island, over and above the long-term background accidental death risk and due to dangers from other natural hazards. Because of the multiplicity of possible volcanic hazards, relative to other sources of risk, the evaluation of such risk levels is complex; a nonlinear relationship exists between the estimates of IRPA shown in Figure 11.11 and the societal curves in Figure 11.10, making it difficult to connect values from one to the other uniquely across all circumstances. This dichotomy adds to the challenges faced by decision-makers and, as yet, no satisfactory way of utilising both forms of risk measure has been found for policy setting in Montserrat or, indeed, further afield (see e.g. Jonkman *et al*., 2011 for a Dutch national flood-risk policy discussion). In Montserrat the civil authorities have to-date been inclined to pay more attention to IRPA values as a criterion for mitigation measures.

Although the Soufrière Hills eruption is the only volcanic crisis so far where these methods have been applied so extensively, there has been a major surge in research in this arena. Hazard and risk assessment methods are starting to be used in mitigation and planning. Vesuvius and the neighbouring Campi Flegri volcano in particular have been the focus of intense research in the EU EXPLORIS Project (Neri *et al*., 2008) and by scientists at the Istituto Nazionale di Geofisica e Vulcanologia (INGV). The INGV has been at the forefront of advanced numerical modelling of hazardous volcanic flows and in integrating such models with vulnerability indices (populations and building quality) to assess risk in the Naples region (Baxter *et al*., 2008). Further EU projects are tackling related aspects of volcano processes and volcanic hazards (e.g. VOLUME TTC; MIAVITA).

A more global and regional approach to volcanic hazard and risk assessment has been pioneered by the National Volcano Early Warning System (NVEWS) method (Ewert and Harpel, 2004; Ewert *et al*., 2005). Here, volcanoes are characterised according to their level of threat, which involves a scoring system for hazard, monitoring capacity and population exposure. The NVEWS method has been adapted for developing-world countries by Aspinall *et al*. (2011) in a study for the GDFRR (World Bank). They define indices for hazard, uncertainty and population exposure for individual volcanoes. These indices are then used to identify high-risk volcanoes. Another example of this emerging arena of volcanic risk and threat mapping is provided by Simpson *et al*. (2011). These approaches are suitable for understanding the state of knowledge, characterising relative levels of risk or threat between volcanoes, identifying knowledge gaps and documenting coping capacity in a particular country or region. They are not appropriate for assessing detailed hazards and risk around individual volcanoes.

11.5 Risk management and communication

Effective risk management during periods of volcanic unrest and eruption is essential to saving lives and minimising losses. Here, science provides critical information for decision-making and responses, such as evacuations. In many cases decisions have to be made at very short notice and good communications between scientists, responsible authorities and affected citizens are pivotal. This section explores some of the main issues and what can be learned from some past volcanic emergencies.

11.5.1 Risk management

Risk management around active volcanoes is required right through what is sometimes called the disaster cycle. In periods of dormancy, risk management activities include assessing the hazards, improving monitoring and early warning systems, land-use planning, raising awareness of volcanic hazards and risk among citizens and development of evacuation plans in the event of an impending eruption. In periods of volcanic unrest that might lead to an eruption there is heightened awareness and emergency planning among authorities, emergency services, scientific institutions (commonly associated with a volcano observatory) and the public. These activities become even more prominent once an eruption starts. Commonly, decisions have to be made very quickly – for example, on whether to evacuate. For persistently active volcanoes the management will be a long-term requirement to enable the society to live safely with the volcano, with emergency situations being declared when the activity becomes heightened. In the recovery period after a crisis lessons learned can be applied to improve future responses, an activity that is probably likely to be more effective if recriminations are avoided. A critical issue is at what stage evacuated people are allowed to return home and rebuilding of disrupted lives and economies can begin. In some cases discussions will be necessary to decide whether it is wise to reoccupy areas of high hazard and relocation of people may become necessary.

In practice, risk management around active volcanoes can become immensely complicated due to many factors unrelated to the physical hazards. Conflicting views and tensions can arise between authorities, scientists and communities for many different reasons. A volcanic eruption is a traumatic and highly disruptive event in which attitudes to and perceptions of risk can vary widely between individuals, institutions, authorities and other elements of civil society (Johnston *et al*., 1999; Paton *et al*., 2001; Davis *et al*., 2005). Authorities taking on emergency powers can come into conflict with individuals who feel their human rights are being infringed. Responses of individuals, communities, societal organisations and institutions and governing authorities include denial, being risk averse and being a risk taker based on perceived benefits from taking risks. In all cases there will be unique cultural, political and economic factors that influence how risk is managed, or not, in a particular circumstance. The Soufrière Hills eruption on Montserrat (1995 to the present) illustrates many of these complexities, and readers are referred to Haynes (2006) for a synthesis of that case history.

One of the major problems for volcanic risk management relates to the ability of scientists to make confident forecasts of impending hazardous activity and the authorities to respond by taking action such as evacuation.

As already discussed in detail earlier, time periods for precursory unrest and low-level activity to build to hazardous eruptions can vary greatly from many years to only a few hours. More often than not, increasing unrest does *not* lead to an eruption, but when the volcano is on an inevitable path to eruption the period of time during which unrest causes meaningful concern may be rather short.

While increasingly supported by better scientific data and improved models, judgement remains central to scientific assessment in such circumstances. On the other hand, decision-making and implementation of these decisions takes time and it is an unfortunate fact that some volcanoes ramp up to dangerous eruptions in times that can be much shorter than the ability of authorities to make and implement mitigation decisions. A future eruption of Vesuvius is an example of a severe issue because evacuation of over 600 000 people from around the flanks of the volcano will take many days, even under the most optimistic assumptions, whereas it is quite likely that the build up to the eruption will be shorter. The common mismatch in timescales leads inevitably to what are sometimes called false alarms, as many government authorities are likely to take a precautionary approach and instigate evacuation orders well before there is complete certainty that an eruption will take place. The 1976 evacuation of the town of Basse Terre in Guadeloupe is the best-known case, when 73 000 people were moved away for three months due to strong seismic unrest and vigorous explosive phreatic activity at the nearby La Soufrière de la Guadeloupe volcano. The fear was a major explosive eruption with pyroclastic flows. At the time there was much controversy and a widespread view in the communities and among some scientists that the evacuation had been unnecessary. In retrospect, the evacuation was a sensible and precautionary decision, but there was much loss of credibility and trust for scientists, which still resonates on the island. Ironically, this 'non-event' may make the communities on the island more vulnerable to a future eruption of La Soufrière.

Because evacuation is the only effective response to dangerous volcanic activity, evacuation modelling (Marzocchi and Woo, 2007; Woo, 2008) is a new area of research for volcanology, with the potential of providing key input into planning for volcanic emergencies. Marzocchi and Woo (2007) have developed a probabilistic scheme that integrates eruption forecasting and cost–benefit analysis of evacuation options. The method incorporates available knowledge on hazards into a quantitative decision-analysis framework using transparent rules. The approach enables prior scrutiny of any scientific input into the model and so may help to reduce the stress on scientists during an emergency phase. Modelling of this kind, however, poses some significant research challenges, as predicting what happens on the ground after an evacuation decision has been made is very difficult because it will likely depend critically on human behaviour. The extent to which human behaviour and economic disruption can be incorporated into evacuation models is problematic and likely contentious.

Evacuation is always traumatic as people have to abandon their homes, belongings and livelihoods at short notice, often under conditions of fear, anxiety and chaos. In general, evacuees are placed in emergency accommodation of some kind and it is often not possible for them, or for the volcanologists, to be sure when they may be able to return, if at all. Prior relocation is becoming increasingly used as a mitigation policy by some governments. Usually this policy is developed during or after an event, when it becomes clear that the evacuated area is going to remain too dangerous to reoccupy. In the case of Galeras in Colombia the government has passed a law to relocate communities living in areas deemed to be at high risk. Whether the policy is evacuation, reoccupation or relocation, the decisions are rarely straightforward and can become contentious and politically charged: scientific uncertainty is an ever-present factor.

11.5.2 Communication

The previous discussion of risk management implies a critical role for communication between key actors before, during and after a volcanic emergency. Scientists are inevitably at the centre of communication networks in that they have specialist knowledge about the potential hazards, the information needed for giving early warning, and informed experience necessary for assessing hazards and risk. Some of the major volcanic disasters reflect communications failure. Analysis of the 1985 Nevado del Ruiz tragedy by Voight *et al.* (2012), when over 23 000 people were killed in the town of Armero, Colombia by a lahar, suggests that factors that contributed were: delays in producing a hazard map; inadequately prepared local authorities; an unprepared populace; and a refusal to accept false alarms. Voight *et al.* (2013) identify the lessons learned at Nevado del Ruiz as: scientists and authorities having to accept the responsibility to communicate the risk to the public; the need to plan critical decisions in advance; to test warning systems in advance; to anticipate technological problems with communication systems; and to develop effective relationships with the media. Similar lessons relating to the importance of effective communication systems were drawn from the 1994–1998 eruptions of Merapi, Indonesia (Voight *et al.*, 2000a).

However, volcanic eruptions at most volcanoes are infrequent and very large eruptions extremely rare, such that they are commonly outside the experience of most official decision-makers and populations. Even with recent efforts to inform people with videos and documentary programmes, it is still difficult to convey the full extent, subtleties and dangers of the hazards that volcanoes can produce. Without previous experience of an eruption, at-risk communities can only make inferences from events elsewhere as to what may happen when their volcano erupts and this may be vastly different. This is not to say that a population with recent experience of volcanic activity necessarily has a more accurate perception of future hazard. If the previous hazard experience was relatively benign, people can experience a ‘normalisation bias’ (Mileti and O’Brien, 1993) whereby this becomes the archetypal eruption, even if there is a strong likelihood of the volcano erupting more violently in the future. A recent example of this situation is the October–November 2010 eruption of Merapi volcano in Indonesia, where quite frequent episodes of pyroclastic flows in the last 100 years had led to hazards zonation and evacuation plans that extended to 10 km from the volcano. Past history, though, suggested that Merapi can have much more energetic and larger magnitude eruptions (Voight *et al.*, 2000b), the last major one prior to 2010 being in the 1800s. The 2010 eruption produced pyroclastic flows, one of which ran out to 17 km, and hazard zonations had to be extended urgently to 20 km during the crisis.

Volcanic eruptive processes are intrinsically unpredictable, and therefore scientists are limited in what they can say with confidence about any future volcanic activity. This uncertainty is sometimes not understood and can be seen by some as incompetence. Conversely, some people can be overly reliant on scientists to provide an adequate warning. For example, in relation to earthquake hazards, investigations conducted by Valery (1995) after the Kobe, Japan, earthquake found that many citizens knew about the risks and how to prepare but believed that the science was so advanced that they would receive a warning before the earthquake struck, so there was no real need to prepare. By contrast, people may become so used to volcanic activity that they become overconfident in their own ability to judge the threat. This seems to have happened in the case of the eruption of the Soufrière Hills volcano on 25 June 1997, when 20 people were killed in the exclusion zone; interviews with survivors (Loughlin *et al*., 2002b) indicate that most understood the risks but were prepared to accept them for the benefits of looking after their farms or property. A similar situation has been found for Etna, where surveys of citizens indicate an objective and informed perspective concerning the volcanic hazard (Davis *et al*., 2005). In contrast, people living in the highest risk areas at Vesuvius showed high levels of fear and perceived risk, but low levels of perceived ability to protect themselves from the effects of an eruption, as well as low levels of awareness concerning evacuation plans and confidence in the success of such plans (Davis *et al*., 2005). This combination of scientific uncertainty, limited hazard experience of the local population and mismatches between public and scientific evaluations of risk represent challenges for effective communication.

Compounded with this are official and political concerns about the best way to provide advice to a threatened population. Officials are sometimes wary of giving vivid descriptions of worst-case scenarios to the public, fearing widespread panic. Officials routinely may expect the public to panic or, at best, to misinterpret orderly efforts to mitigate disaster. Thus, being anxious not to create panic can lead officials to make over-reassuring statements, to suppress information, sometimes contradicting scientific advice, and to belittle those who are anxious as irrational (see also Chapter 16). On the other hand, public officials can also be afraid of being blamed in the case of casualties and therefore can take a precautionary, risk-averse approach. A balance needs to be struck between reassuring the population that any future crisis will be dealt with and arousing enough interest in the subject that complacency does not set in. This is particularly pertinent for volcanic hazards where there can be very long periods of quiescence between eruptions. Unfortunately there are few published analyses of these issues for volcanic crises, but useful insights can be gained from health fears (Leventhal, 1971).

It is imperative that the goals of communication are properly defined before attempting to communicate risks relating to volcanic hazards, or any other hazard for that matter. Is the aim to simply inform about the hazards and potential mitigative actions that can be taken, or is it to effect behaviour change? Moreover, who will be responsible for such communication? It has long been believed that scientists should be responsible for monitoring and prediction, whereas the government or emergency management officials should be those who communicate the necessary information, along with whatever policy decisions they draw from this information, to the public (Peterson and Tilling, 1993; Peterson, 1996). However, scientists are becoming more and more involved in the communication of at least the hazard information, if not risk; for example, at Mount St Helens (Driedger *et al*., 2008; Frenzen and Matarrese, 2008). There is no single model for risk communication that will work in all situations, as both the hazard and the political situations vary from one location to another, and so the communication methods will also need to adapt.

That being said, one of the principal challenges for good risk communication is to instil trust in those who are responsible for public safety and risk communication, particularly when personal experience is lacking (Renn and Levine, 1991). Research in this area conducted on three separate islands in the Lesser Antilles, each in different stages of unrest, had similar findings with regard to trust in scientists; they were found to be one of the most trustworthy sources, ranked significantly higher than the local governments on each of the islands (see Haynes *et al.*, 2008; Crosweller, 2009). Much of this can be explained through the fact that scientists are often seen as being 'value neutral'. Trust, however, is fragile and is much easier to lose than it is to gain, and so every effort must be made to communicate clearly about the uncertainties and limitations of scientific predictions. It should be made clear that unfulfilled alarms will be likely in any crisis management. This issue of unfulfilled warnings is also an important point for the scientific community to grapple with: scientists, by inclination, will seek to find very reliable prediction and forecast methods, because that is the basis for scientific progress, almost to the point of requiring nothing less than a physical law before making predictions. However, total reliability of predictions or forecasts is never going to be achievable, and good risk communication and management needs to accommodate uncertainties in the best ways possible, and this means taking advantage of emerging 'evidence science' theories and methods (Aspinall *et al.*, 2003), which are finding application in many safety-critical fields where scientific uncertainty is a present and key factor. It also requires a readiness on the part of officials and the public to accept some 'false alarms' if they require a high degree of safety. In effect, social contracts between scientists, officials and those at risk are needed.

We live in a world of rapid changes in communication with mobile phones, the internet and social networking augmenting, and to some extent replacing, traditional ways of communication. There are certainly opportunities for innovation as well as new challenges. In recent volcanic emergencies the 'new media' played a key role in the dissemination of information and, unfortunately, misinformation. New forms of communication, such as the blogosphere, Twitter and mobile phones provide opportunities to disseminate scientific advice, early warnings and raise awareness. On the other hand, they also allow the spreading of unfounded rumours, the promotion of antagonistic scepticism against mainstream science and other contrarian views, and enable conspiracy theories to proliferate at lightning speed. Working more closely with the media and with these new forms of communication is going to be essential, but challenging.

11.6 Future outlook and challenges

Advances in enabling technologies and understanding of volcanic processes over the last decade have greatly enhanced the ability of volcanologists to anticipate the behaviour of volcanoes and to assess their hazards. However, application of these advances to forecasting and emergency management during eruptions is contingent on having suitable resources in place, and this is not necessarily the case in developing countries, where many volcanoes remain poorly monitored and other priorities exist for limited resources. Reduction in costs of electronic equipment and increasing availability of remotely sensed observations are helping to improve the monitoring status of many volcanoes. Methodologies to assess hazards footprints in probabilistic terms have developed together with quantitative approaches to risk assessment. The importance of evaluating uncertainties is becoming ever more apparent.

This said, there is a significant gulf between quite advanced academic research and routine practice in 'applied volcanology'. Academic research is thriving in terms of the development of physics-based models of hazardous volcanic processes and advanced statistical approaches to risk assessment and treatment of uncertainty. Most volcanic crises are still handled using the traditional tools of hazards mapping and forecasting based on monitoring. Observations and knowledge of past eruptive activity are valuable, but interpretation of the underlying processes and future behaviour is difficult and uncertain and requires an approach that uses all the advanced science available and more robust statistical treatment. Risk and uncertainty are often dealt with qualitatively and there remains a conservative element among practitioners and some observatory scientists who do not see the value in trying to quantify either. Examples in the UK (with Montserrat), New Zealand and Italy show this situation is going to change as more practitioners are trained in research groups in the expertise and skills to assess risk quantitatively. However, much still needs to be done to train young scientists and educate the older generation of scientists in the methods of analysis and communication of risk and related uncertainties.

Volcanologists are increasingly being asked to go beyond traditional roles of monitoring, hazard assessment, giving early warning and providing scientific advice, and are increasingly being called upon to participate in risk assessment applied to decision-making. These pressures reflect a broader trend for science to be more actively engaged in addressing societal problems but will bring scientists into new and more complex arenas and roles. There is certainly some discomfort for many. Volcanologists have the expertise to quantify hazard and risk as well as attendant uncertainties, but as many social scientists would remark, risk is essentially a human construct. Volcanologists must work with engineers, other technical experts and social scientists to make full assessments of volcanic risk. There are also limits to the benefits of such quantification and indeed the ability to quantify some facets of risk. Volcanologists can estimate the risk and uncertainties of loss of life, given assumptions about the hazard and the location of people, but what is much harder to quantify is how people will respond to, for example, evacuation orders. The meaning of 'risk', which is intrinsically multifaceted, needs to be articulated, not least because there is some concern that attempts to quantify risk in support of public safety may also open up its practice to litigation if things go 'wrong'.

Risk management for volcanoes has largely been viewed in terms of emergency response, with the goal of avoiding loss of life. The priority accorded to this perspective is not likely to change soon. However, there is increasing attention being paid to better planning so that economic losses and loss of life are reduced. In the arena of development, reducing the impact of natural disasters on sustainable livelihoods is becoming a higher priority, and so approaches that increase the resilience of communities is now the *lingua franca* of discussions. This has provoked, rightly, many questions about what is the best approach to volcanic risk mitigation and the political or economic impact of volcanic disasters. A repeated narrative for natural disasters is that society has hitherto tended to be reactive rather than proactive. In the future it seems likely that the role of scientists will become more complex, and challenging, as they are drawn deeper into risk assessment and forecasting the future.

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References

Aspinall, W. P. and Cooke, R. (1998) Expert judgement and the Montserrat volcano eruption. In *Proceedings of the 4th International Conference on Probabilistic Safety Assessment and Management PSAM4, 13–14 September 1998*, ed. A. Mosleh. and R. A. Bari, New York: Springer.

Aspinall, W. P., Woo, G., Voight, B., *et al.* (2003) Evidence-based volcanology: application to eruption crises. *Journal of Volcanology and Geothermal Research* **128**: 273–285.

Aspinall, W. P., Auker, M., Hincks, T., *et al.* (2011) Volcanic hazard and risk in GDRFF priority countries. NGI report 20100806, May. http://www.globalvolcanomodel.org.

Baubron, J.-C., Allard, P., Sabroux, J-C., *et al.* (1991) Soil gas emanations as precursory indicators of volcanic eruptions. *Journal of the Geological Society* **148**: 571–576.

Baxter, P. J. (1990) Medical effects of volcanic eruptions. *Bulletin of Volcanology* **52**: 532–544.

Baxter, P. J., Aspinall, W. P., Neri, A., *et al.* (2008) Emergency planning and mitigation at Vesuvius: a new evidence-based approach. *Journal of Volcanology and Geothermal Research* **178**: 454–473.

Bebbington, M., Cronin, S. J., Chapman, I., *et al.* (2008) Quantifying ash fall hazard to electrical infrastructure. *Journal of Volcanology and Geothermal Research* **177**: 1055–1062.

Biggs, J., Amelung, F., Gourmelen, M., *et al.* (2009) InSAR observations of 2007 Tanzania rifting episode reveal mixed fault and dyke extension in an immature continental rift. *Geophysical Journal International* **179**: 549–558.

Blong, R. J. (1984) *Volcanic Hazards: A Source Book on the Effects of Eruptions*, Orlando, FL: Academic Press Inc.

Bonadonna, C., Macedonio, G. and Sparks, R. S. J. (2002) Numerical modelling of tephra fallout associated with dome collapses and Vulcanian explosions: application to hazard assessment on Montserrat. In *The Eruption of the Soufrière Hills Volcano, Montserrat 1995 to 1999*, ed. T. H. Druitt and B. P. Kokelaar, London: Geological Society of London, pp. 517–538.

Bryan, S. E., Peate, I. U., Peate, D. W., *et al.* (2010) The largest volcanic eruptions on Earth. *Earth-Science Reviews* **102**: 207–229.

Burgmann, R., Rosen, P. A. and Fielding, E. J. (2000) Synthetic aperture radar interferometry to measure Earth's surface topography and its deformation. *Annual Review of Earth and Planetary Sciences* **28**: 169–209.

Burton, M. R., Allard, P., Murè, F., *et al.* (2007) Magmatic gas composition reveals the source of Strombolian explosive activity. *Science* **371**: 227–230.

Carn, S. A., Krueger, A. J., Krotkov, N. A., *et al*. (2008) Daily monitoring of Ecuadorian volcanic degassing from space. *Journal of Volcanology and Geothermal Research* **176**: 141–150.

Charbonnier, S. J. and Gertisser, R. (2009) Numerical simulations of block-and-ash flows using the Titan2D flow model: examples from the 2006 eruption of Merapi Volcano, Java, Indonesia. *Bulletin of Volcanology* **71**: 953–959.

Clay, E., Barrow, C., Benson, C., *et al*. (1999) *An Evaluation of HMG's Response to the Montserrat Volcanic Emergency*, London: DFID.

Connor, C. B., Chapman, N. and Connor, L. J. (eds) (2009) *Volcanism, Tectonism and the Siting of Nuclear Facilities*, Cambridge: Cambridge University Press.

Costa, A., Macedonio, G. and Folch, A. (2006) A three-dimensional Eulerian model for transport and deposition of volcanic ashes. *Earth Planetary Science Letters* **241**: 634–647.

Costa, A., Dell'Erba, F., Di Vito, M., *et al*. (2009) Tephra fallout hazard assessment at the Campi Flegrei caldera (Italy). *Bulletin of Volcanology* **71**: 259–273.

Crosweller, H. S. (2009) An analysis of factors influencing volcanic risk on two islands in the Lesser Antilles. PhD thesis, University of East Anglia.

Dalton, M. P., Waite, G. P., Watson, I. M., *et al*. (2010) Multiparameter quantification of gas release during weak Strombolian eruptions at Pacaya Volcano, Guatemala. *Geophysical Research Letters* **37**: L09303.

Davis, M. S., Ricci, T. and Mitchell, L. M. (2005) Perceptions of risk for volcanic hazards at Etna and Vesuvio. *The Australian Journal of Disaster and Trauma Studies*. http://www.massey.ac.nz/~trauma/issues/2005-1/davis.htm

Deligne, N. I., Coles, S. G. and Sparks, R. S. J. (2010) Recurrence rates of large explosive volcanic eruptions. *Journal of Geophysical Research* **115**: B06203.

Driedger, C. L., Neal, C. A., Knappenberger, T. H., *et al*. (2008) Hazard information management during the autumn 2004 reawakening of Mount St. Helens Volcano, Washington. In *A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006*, US Geological Survey Professional Paper 1750, ed. D. R. Sherrod, W. E. Scott and P. H. Stauffer, Chapter 24.

Durant, A. J., Bonadonna, C. and Horwell, C. J. (2010) Atmospheric and environmental impacts of volcanic particulates. *Episodes* **6**: 235–240.

Dzurisin, D. (2003) A comprehensive approach to monitoring volcano deformation as a window on the eruption cycle. *Reviews of Geophysics* **41**: 1001.

Edmonds, M. (2008) New geochemical insights into volcanic degassing. *Philosophical Transactions of the Royal Society A* **366**: 4559–4579.

Ewert, J. W. and Harpel, G. J. (2004) In harm's way: population and volcanic risk. *Geotimes* **49**: 14–17.

Ewert, J. W., Guffanti, M. and Murray, T. L. (2005) An assessment of volcanic threat and monitoring capabilities in the United States: framework for a National Volcano Early Warning System (NVEWS). USGS Open-File Report 2005–1164.

Feuillard, M., Allegré, C. J., Brandeis, G., *et al*. (1983) The 1975–1977 crisis of La Soufrière de Guadeloupe (F.W.I.): a still-born magmatic eruption. *Journal of Volcanology and Geothermal Research* **16**: 317–334.

Fiske, R. (1984) Volcanologists, journalists, and the concerned local public: a tale of two crises in the eastern Caribbean. In *Explosive Volcanism: Inception, Evolution and Hazards. Studies in Geophysics*, ed. F. Boyd, Washington, DC: National Academy Press, pp. 170–176.

Frenzen, P. M. and Matarrese, M. T. (2008) Managing public and media response to a reawakening volcano: lessons from the 2004 eruptive activity of Mount St. Helens.

A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006, US Geological Survey Professional Paper 1750, ed. D. R. Sherrod, W. E. Scott and P. H. Stauffer, Chapter 23.
Galle, B., Oppenheimer, C., Geyer, A., *et al*. (2003) A miniaturised ultraviolet spectrometer for remote sensing of SO_2 fluxes: a new tool for volcano surveillance. *Journal of Volcanology and Geothermal Research* **119**: 241–254.
Geshi, N., Kusumoto, S. and Gudmundsson, A. (2010) Geometric difference between non-feeder and feeder dikes. *Geology* **38**: 195–198.
Grattan, J. P. (2006) Aspects of Armageddon: an exploration of the role of volcanic eruptions in human history and civilization. *Quaternary International* **151**: 10–18.
Grattan, J. P. and Charman, D. J. (1994) Non-climatic factors and the environmental impact of volcanic volatiles: implications of the Laki Fissure eruption of AD 1783. *The Holocene* **4**: 101–106.
Hansell, A. L., Horwell, C. J. and Oppenheimer, C. (2006) The health hazards of volcanoes and geothermal areas. *Occupational and Environmental Medicine* **63**: 149–156.
Hautmann, S., Gottsmann, J., Sparks. R. S. J., *et al*. (2010) The effect of mechanical heterogeneity in arc crust on volcano deformation with application to Soufrière Hills Volcano, Montserrat (W.I.). *Journal of Geophysical Research* **115**: B09203.
Haynes, K. A. (2006) Volcanic island in crisis: investigating environmental uncertainty and the complexities it brings. *The Australian Journal of Emergency Management* **21** (4): 21–28.
Haynes, K. A., Barclay, J. and Pidgeon, N. (2008) The issue of trust and its influence on risk communication during a volcanic crisis. *Bulletin of Volcanology* **70**: 605–621.
Heilprin, A. (1903) *Mont Pelée and the Tragedy of Martinique: A Study of the Great Catastrophes of 1902, with Observations and Experiences in the Field*, Philadelphia, PA: J.B. Lippincott Company.
Hill, B. E., Aspinall, W. P., Connor, C. B., *et al*. (2012) Recommendations for assessing volcanic hazards at sites of nuclear installations. In *Volcanic and Tectonic Hazard Assessment for Nuclear Facilities*, ed. C. B. Connor, N. A. Chapman and L. J. Connor, Cambridge: Cambridge University Press, pp. 566–592.
Hincks, T. K., Aspinall, W. P., Baxter, P. J., *et al*. (2006) Long-term exposure to respirable volcanic ash on Montserrat: a time series simulation. *Bulletin of Volcanology* **68**: 266–284.
IATA (International Air Transport Association) (2011) *Annual Report 2011*, http://www.iata.org/pressroom/Documents/annual-report-2011.pdf.
Iverson, R. M., Schilling, S. P. and Vallance, J. W. (1998) Objective delineation of lahar-inundation zones. *Geological Society of America Bulletin* **110**: 972–984.
Johnston, D. M., Bebbington, M. S., Lai, C.-D., *et al*. (1999) Volcanic hazard perceptions: comparative shifts in knowledge and risk. *Disaster Prevention and Management* **8**: 118–126.
Jonkman, S. N., Jongejan, R. and Maaskant, B. (2011) The use of individual and societal risk criteria within the Dutch Flood Safety Policy: nationwide estimates of societal risk and policy applications. *Risk Analysis* **31**: 282–300.
Kerle, N., van Wyk De Vries, B. and Oppenheimer, C. (2003) New insight into the factors leading to the 1998 flank collapse and lahar disaster at Casita Volcano, Nicaragua. *Bulletin of Volcanology* **65**: 331–345.
Komorowski, J.-C., Tedesco, D., Kasereka, M., *et al*. (2003) The January 2002 flank eruption of Nyiragongo volcano (Democratic Republic of Congo): chronology,

evidence for a tectonic rift trigger, and impact of lava flows on the city of Goma. *Acta Vulcanologica* **15**: 27–61.

Leventhal, H. (1971) Fear appeals and persuasion: the differentiation of a motivational construct. *American Journal of Public Health* **61**: 1208–1224.

Linde, A. T., Agustsson, K., Sacks, I. S., *et al*. (1993) Mechanism of the 1991 eruption of Hekla from continuous borehole strain monitoring. *Nature* **365**: 737–740.

Lindsay, J., Marzocchi, W., Jolly, G., *et al*. (2010) Towards real-time eruption forecasting in the Auckland Volcanic Field: application of BET_EF during the New Zealand national disaster exercise 'Ruaumoko'. *Bulletin of Volcanology* **72**: 185–204.

Loughlin, S. C., Calder, E. S., Clarke, A., *et al*. (2002a) Pyroclastic flows and surges generated by the 25 June 1997 dome collapse, Soufriere Hills Volcano, Montserrat. In *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*, ed. T. H. Druitt and B. P. Kokelaar, London: Geological Society of London, pp. 191–209.

Loughlin, S. C., Baxter, P. J., Aspinall, W. P., *et al*. (2002b) Eyewitness accounts of the 25 June 1997 pyroclastic flows and surges at Soufrière Hills Volcano, Montserrat, and implications for disaster mitigation. *In The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*, ed. T. H. Druitt and B. P. Kokelaar, London: Geological Society of London, pp. 211–230.

Marzocchi, W. and Woo, G. (2007) Probabilistic eruption forecasting and the call for an evacuation. *Geophysical Research Letters* **34**: L22310.

Marzocchi, W. and Woo, G. (2009) Principles of volcanic risk metrics: theory and the case study of Mount Vesuvius and Campi Flegrei, Italy. *Journal of Geophysical Research* **114**: n.p.

Marzocchi, W., Sandri, L., Gasparini, P., *et al*. (2004) Quantifying probabilities of volcanic events: the example of volcanic hazard at Mt. Vesuvius. *Journal of Geophysical Research* **109**: B11201.

Marzocchi, W., Sandri, L. and Selva, J. (2008) BET_EF: a probabilistic tool for long- and short-term eruption forecasting. *Bulletin of Volcanology* **70**: 623–632.

Marzocchi, W., Sandri, L. and Selva, J. (2010) BET_VH: a probabilistic tool for long-term volcanic hazard assessment. *Bulletin of Volcanology* **72**: 705–716.

Mason, B. G., Pyle, D. M. and Oppenheimer, C. (2004) The size and frequency of the largest explosive eruptions. *Bulletin of Volcanology* **66**: 735–748.

Mather, T. A. and Harrison, R. G. (2006) Electrification of volcanic plumes. *Surveys in Geophysics* **27**: 387–432.

McNutt, S. R. (2005) Volcano seismology. *Annual Reviews of Earth and Planetary Sciences* **32**: 461–491.

Mileti, D. S. and O'Brien, P. W. (1993) Public response to aftershock warnings. US Geological Survey Professional Paper 1553-B, pp. 31–42.

Mogi, K. (1958) Relations between the eruptions of various volcanoes and the deformations of the ground surfaces around them. *Bulletin of Earthquake Research Institute University of Tokyo* **36**: 99–134.

Moran, S., Newhall, C. G. and Roman, D. (2011) Failed eruptions; late stage cessation of magma ascent. *Bulletin of Volcanology* **73**: 115–122.

Neri, A., Aspinall, W. P., Cioni, R., *et al*. (2008) Developing an event tree for probabilistic hazard and risk assessment at Vesuvius. *Journal of Volcanology and Geothermal Research* **178** (3): 397–415.

Newhall, C. G. and Dzurisin, D. (1988) *Historical Unrest at Large Calderas of the World*, Washington, DC: US Government Print Office.

Newhall, C. G. and Hoblitt, R. P. (2002) Constructing event trees for volcanic crises. *Bulletin of Volcanology* **64**: 3–20.
Newhall, C. G. and Punongbayan, R. S. (1996a) The narrow margin of successful volcanic-risk mitigation. In *Monitoring and Mitigation of Volcanic Hazards*, ed. R. Scarpa and R. I. Tilling, Berlin: Springer-Verlag, pp. 807–838.
Newhall, C. G. and Punongbayan, R. (eds) (1996b) *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines*. Quezon City and Seattle, WA: Philippine Institute of Volcanology and Seismology and University of Washington Press.
Newhall, C. G. and Self, S. (1982) The volcanic explosivity index (VEI): an estimate of explosive magnitude for historical volcanism. *Journal of Geophysical Research* **87**: 1231–1238.
Paton, D., Johnston, D. and Houghton, B. (2001) Direct and vicarious experience of volcanic hazards: implications for risk perception and adjustment adoption. *Australian Journal of Emergency Management* **15**: 58–63.
Peterson, D. W. (1996) Mitigation measures and preparedness plans for volcanic emergencies. In *Monitoring and Mitigation of Volcano Hazards*, ed. R. Scarpa and R. I. Tilling, Berlin: Springer-Verlag, pp. 701–718.
Peterson, D. W. and Tilling, R. I. (1993) Interactions between scientists, civil authorities and the public at hazardous volcanoes. *Active Lavas*, ed. C. R. J. Kilburn and G. Luongo, London: UCL Press, pp. 339–365.
Poland, M. (2010) Learning to recognise volcanic non-eruptions. *Geology* **38**: 287–288.
Pritchard, M. E. and Simons, M. (2004) An InSAR-based survey of volcanic deformation in the central Andes. *Geochemistry Geophysics Geosystems* **5**: n.p.
Punongbayan, R. S., Newhall, C. G., Bautista, L. P., *et al.* (1996) Eruption hazard assessments and warnings. In *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines*, ed. C. G. Newhall and R. Punongbayan, Quezon City and Seattle, WA: Philippine Institute of Volcanology and Seismology and University of Washington Press.
Rampino, M. (2002) Supereruptions as a threat to civilizations on Earth-like planets. *Icarus* **156**: 562–569.
Renn, O. and Levine, D. (1991) Credibility and trust in risk communication. In *Communicating Risks to the Public: International Perspectives*, ed. R. E. Kasperson and P. J. M. Stallen, Dordrecht: Kluwer Academic Publishers, pp. 175–218.
Robertson, R. E. A., Aspinall, W. P., Herd, R. A., *et al.* (2000) The 1995–98 eruption of the Soufriere Hills volcano, Montserrat. *Philosophical Transactions of the Royal Society* **358**: 1619–1637.
Robock, A. (2000) Volcanic eruptions and climate. *Reviews of Geophysics* **38**: 191–219.
Sandri, L., Guidoboni, E., Marzocchi, W., *et al.* (2009) Bayesian Event Tree (BET) for eruption forecasting at Vesuvius, Italy: a retrospective forward application to 1631 eruption. *Bulletin of Volcanology* **71**: 729–745.
Saucedo, R., Macias, J. L., Sheridan, M. F., *et al.* (2005) Modelling of pyroclastic flows of Colima Volcano, Mexico: implications for hazard assessment. *Journal of Volcanology and Geothermal Research* **139**: 103–115.
Schilling, S. (1998) LAHARZ: GIS Programs for Automated Mapping of Lahar-inundation Hazard Zones: U.S. Geological Survey Open-File Report 98–638.
Schneider, D., Delgado Granados, H., Huggel, C., *et al.* (2008) Assessing lahrz from ice-capped volcanoes using ASTER satellite data, the SRTM DTM and two different flow models: case study on Iztaccihuatl (Central Mexico). *Natural Hazards Earth System Science* **8**: 559–571.

Selva, J., Costa, A., Marzocchi, W., *et al*. (2010) BET_VH: exploring the influence of natural uncertainties on long-term hazard from tephra fallout at Campi Flegrei (Italy). *Bulletin of Volcanology* **72**: 717–733.

Siebert, L., Simkin, T. and Kimberly, P. (2011) *Volcanoes of the World*, 3rd edn, Washington, DC: University of California Press.

Simkin, T., Siebert, L. and Blong, R. (2001) Volcano fatalities: lessons from the historical record. *Science* **291**: 255.

Simpson, A., Johnson, W. R. and Cummins, P. (2011) Volcanic threat in developing countries of the Asia-Pacific region: probabilistic hazard assessment, population risks, and information gaps. *Natural Hazards* **57**: 151–165.

Small, C. and Naumann, T. (2001) The global distribution of human population and recent volcanism. *Environmental Hazards* **3**: 93–109.

Sparks, R. S. J. (2003) Forecasting volcanic eruptions. *Earth and Planetary Science Letters, Frontiers in Earth Science Series* **210**: 1–15.

Sparks, R. S. J. and Aspinall, W. P. (2004) Volcanic Activity: Frontiers and Challenges in Forecasting, Prediction, and Risk Assessment, Washington, DC: American Geophysical Union.

Sparks, R. S. J., Bursik, M. I., Carey, S. N., *et al*. (1997) *Volcanic Plumes* Chichester: John Wiley and Sons.

Sparks, R. S. J., Self, S., Grattan, J., *et al*. (2005) Super volcanoes: global effects and future threats. Geological Society of London, Report of a Working Group, June.

Sparks, R. S. J., Biggs, J. and Neuberg, J. W. (2012) Monitoring volcanoes. *Science* **335**: 1310–1311.

Spence, R., Kelman, I., Baxter, P., *et al*. (2005) Residential building and occupancy vulnerability to tephra fall. *Natural Hazards and Earth Systems Science* **5**: 477–494.

Thomas, H. E. and Watson, I. M. (2010) Observations of volcanic emissions from space: current and future perspectives. *Natural Hazards* **54**: 323–354.

Thomas, H. E., Watson, I. M., Kearney, C. K., *et al*. (2009) A multi-sensor comparison of sulphur dioxide emissions from the 2005 eruption of Sierra Negra volcano, Galápagos Island. *Remote Sensing of Environment* **113**: 1331–1342.

Tilling, R. I. (1989) Volcanic hazards and their mitigation: progress and problems. *Reviews of Geophysics* **27**: 237–269.

Tilling, R. I. and Peterson, L. W. (1993) Lessons in reducing volcanic risk. *Nature* **364**: 277–279.

Todesco, M., Neri, A., Esposti Ongaro, T., *et al*. (2002) Pyroclastic flow hazard assessment at Vesuvius (Italy) by using numerical modeling: I. Large-scale dynamics. *Bulletin of Volcanology* **64**: 155–177.

Ui, T., Matsuwo, N., Sumita, M. and Fujinawa, A. (1999) Generation of block and ash flows during the 1990–1995 eruption of Unzen Volcano, Japan. *Journal of Volcanology and Geothermal Research* **89**: 123–137.

Valery, N. (1995) Fear of trembling: a survey of earthquake engineering. *The Economist* **22**: 3–12.

Van Westen, C. J. and Daag, A. S. (2005) Analysing the relation between rainfall characteristics and lahar activity at Mount Pinatubo, Philippines. *Earth Surface Processes and Landforms* **30**: 1663–1674.

Voight, B. (1990) The 1985 Nevado del Ruiz volcano catastrophe: anatomy and retrospection. *Journal of Volcanology and Geothermal Research* **1**: 349–386.

Voight, B., Glicken, H., Janda, R. J., *et al*. (1981) Catastrophic rock-slide avalanche of May 18. In *The 1980 Eruption of Mount St Helens*, US Geological Survey Professional Paper 1250, ed. P. W. Lipman and D. R. Mullineaux, pp. 347–378.

Voight, B., Constantine, E. K., Siswowidjoyo, S., *et al*. (2000a) Historical eruptions of Merapi Volcano, Central Java, Indonesia, 1768–1998. *Journal of Volcanology and Geothermal Research* **100**: 69–138.

Voight, B., Young, K. D., Hidayat, D., *et al*. (2000b) Deformation and seismic precursors to dome-collapse and fountain-collapse nuées ardentes at Merapi Volcano, Java, Indonesia, 1994–1998. *Journal of Volcanology and Geothermal Research* **100**: 261–287.

Voight, B., Calvache, M. L., Minard, V., Hall, L. and Monsalve, M. L. (2013) The tragic 13 November 1985 eruption of Nevado del Ruiz Volcano, Colombia; the worst can happen. *Encyclopaedia of Natural Hazards* Bobrowsky, P. (ed.) *(in press). Springer Verlag*. ISBN 978-90-481-8699-0.

Wadge, G. (2009) Assessing the pyroclastic flow hazards from dome collapse at Soufriere Hills Volcano, Montserrat. In *Studies in Volcanology: The Legacy of George Walker*, ed. T. Thordarson, S. Self, G. Larsen, *et al*., London: Geological Society, pp. 211–224.

Werner, C. A., Brantley, S. L. and Boomer, K. (2000) CO2 emissions related to the Yellowstone volcanic system 2: statistical sampling, total degassing, and transport mechanisms. *Journal of Geophysical Research* **105**: 10831–10846.

Werner, C., Christenson, B. W., Hagerty, M., *et al*. (2006) Variability of volcanic gas emissions during a crater lake heating cycle at Ruapehu Volcano, New Zealand. *Journal of Volcanology and Geothermal Research* **154**: 291–302.

Widiwijayanti, C., Voight, B., Hidayat, D., *et al*. (2009) Objective rapid delineation of areas at risk from block-and-ash pyroclastic flows and surges. *Bulletin of Volcanology* **71**: 687–703.

Witham, C. (2005) Volcanic disasters and incidents: a new database. *Journal of Volcanology and Geothermal Research* **148**: 191–233.

Woo, G. (2008) Probabilistic criteria for volcano evacuation decisions. *Natural Hazards* **45**: 87–97.